GeoHealth

RESEARCH ARTICLE

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Special Section:
Community Engaged Research to Action: Examples from GeoHealth

Key Points:

- Municipal composting represents an opportunity to transform waste and create media that critically support Urban Agriculture (UA)
- Resuspended legacy Pb from urban soils contaminates urban compost through commonly sourced feedstocks, resulting in elevated Pb levels
- Pb in compost can reach levels of public health concern requiring geochemically informed, health protective benchmarks for compost Pb

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

C. Yang and D. Brabander,
jyang10@wellesley.edu;
dbraband@wellesley.edu

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Municipal Compost Public Health, Waste Management, and Urban Agriculture: A Decadal Study of Fugitive Pb in City of Boston, Massachusetts, USA

Chansie Yang[1,2], Claire Hayhow[3,4], Emma Jackman[3], Danielle Andrews[5], and Daniel Brabander[1,3]

[1]Department of Environmental Studies, Wellesley College, Wellesley, MA, USA, [2]Now at Department of Biology, University of Washington, Seattle, WA, USA, [3]Department of Geosciences, Wellesley College, Wellesley, MA, USA, [4]Now at Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA, [5]The Food Project, Boston, MA, USA

Abstract Compostable materials constitute roughly half of waste generated globally, but only 5% of waste is actually processed through composting, suggesting that expanding compost programs may be an effective way to process waste. Compostable waste, if properly collected and processed, has value-added end use options including: residential and park landscaping, remediation of brownfield sites, and as growing media in urban agriculture (UA). Since 2001, our lab has partnered with The Food Project, a non-profit focused on youth leadership development through urban farming. From 2006 to 2022 we collected compost materials that were delivered to the farm from a variety of local sources and analyzed a suite of biogeochemical properties including lead (Pb) concentrations, organic carbon, and grain size distribution. Pb concentrations of Boston's municipal compost always exceeded the current City of San Francisco soil and compost purchase standard (80 μg/g). In 2012 Boston's composting program was halted when it exceeded the 400 μg/g Environmental Protection Agency's Pb in soil benchmark. Urban Pb is geomobile and must be managed to minimize resuspension and transport of fines whose Pb concentration is often elevated compared to bulk compost. Consequently, urban farmers have to source lower Pb compost from suburban suppliers at significantly greater cost. Over a 15 year period and through several city vendor contracts, Pb concentrations in municipal compost remain at levels that warrant continued surveillance and risk assessment.

Plain Language Summary Locally sourced compost is the life blood of urban agriculture (UA). It is used to fill raised beds, added as a soil amendment to increase carbon contents, and helps manage soil moisture. In the greater Boston area, consistent access to compost low in fugitive lead (Pb) and rich in nutrients is limited. Starting in 2006, our lab began collecting compost delivered to The Food Project, a non-profit urban farm in Dorchester, MA. The Pb concentrations consistently exceeded California's compost benchmark of 80 μg/g and in 2012, Boston's composting program was halted because it exceeded the Environmental Protection Agency Pb in soil benchmark of 400 μg/g. We demonstrate that geochemical fingerprinting management of feedstocks can yield consistent, quality compost. This supports the growing urban farming movement. Rather than treating organic urban waste streams as a problem to manage solely around cost control, design collection and processing approaches must minimize all fugitive contaminants so that these carbon sources can support UA, increase food sovereignty, and promote environmental justice.

1. Introduction

The urban agriculture (UA) movement aims to achieve greater social and environmental justice in urban communities by creating multicultural, intergenerational spaces that address issues of food apartheid (Boggs, 2011; Wortman & Lovell, 2013). Community gardens, guided by values of sustainability, community, and justice, reimagine deindustrialized and disinvested spaces as places to create community and empower people by creating gardens filled with nutritious food while providing space for community art and leisure (Boggs, 1998). Food sovereignty is key to UA and has its foundations in the Black farmers movement, declaring that "we cannot free ourselves until we feed ourselves" (Boggs, 2011).

However, the same systems of oppression that the UA movement acts in resistance to are also responsible for disproportionately contaminating low-income communities and communities of color (Distler & Saikawa, 2020;

Filippelli & Laidlaw, 2010; Filippelli & Taylor, 2018; Kodros et al., 2022; Laidlaw et al., 2022; Morrison et al., 2013; Muller et al., 2018; Pamuk et al., 1998; Raymond & Brown, 2016; Saikawa & Filippelli, 2021; Yeter et al., 2020). Many studies have found that youth from low-income families in urban areas have an increased risk of exposure to heavy metals, with racial and class disparities resulting in greater exposure burden (Distler & Saikawa, 2020; Filippelli & Laidlaw, 2010; Filippelli & Taylor, 2018; Morrison et al., 2013; Muller et al., 2018; Pamuk et al., 1998; Raymond & Brown, 2016; Saikawa & Filippelli, 2021; Yeter et al., 2020). In Boston, this disproportionate burden is due to (a) policies like redlining, which perpetuated racial and economic segregation, creating health disparities in disinvested neighborhoods that experience higher densities of legacy emissions sources (Jung et al., 2022), (b) local corruption, which condoned landlord instigated arson-for-profit schemes that spread aerosolized leaded paint in Boston neighborhoods (Brady, 1983), and (c) a lack of health-protective lead (Pb) in soil benchmarks at the local, state, and national levels (Lupolt et al., 2022).

Turning a waste stream into a useful product has the potential to minimize environmental harms while promoting a shift to a circular economy for waste management (Chen et al., 2020; Wilson & Velis, 2015). Composting remains a high potential avenue for waste management since compostable materials account for nearly half of global waste (Kaza et al., 2018). Compost is rich in organic matter, which may aid stable metal complexation and thereby reduces metal solubility (Pini et al., 2012) and Pb bioaccessibility (Sharp & Brabander, 2017). Many materials, such as biochar, manure, food, and yard waste, have been used with varying levels of efficacy in improving soil quality (Lee et al., 2006; Liang et al., 2017; Sabir et al., 2015; Walker et al., 2004). While compost is a promising waste management strategy, compost quality depends on feedstocks and processing, both of which can introduce fugitive contaminants.

The prevalence of soil pollution means that some common heavy metals like Pb, As, and Cd may be transported to the compost product as fugitive legacy metals, complicating the use of compost as a remedial intervention. Legacy Pb in the urban environment has been widely reported (Biasioli et al., 2007; Spittler & Feder, 1979), with many studies reporting high Pb concentrations from soil in urban gardens (Attanayake et al., 2014; Bugdalski et al., 2014; Cheng et al., 2015; Clark et al., 2006; Clarke et al., 2015; Jean-Soro et al., 2015; McBride et al., 2014). In one case, urban garden soils in Brooklyn, NY reached Pb concentrations up to 45,076 μg/g, over 100 times the current Environmental Protection Agency (EPA) Pb in soil benchmark (Paltseva & Cheng, 2019). The persistence of legacy Pb in urban soil complicates feedstock and poses a challenge for urban agricultural communities seeking food sovereignty and social justice (Wortman & Lovell, 2013).

The Food Project (TFP) is an UA non-profit focused on youth leadership development through urban farming. Its members work in areas of Boston living under food apartheid and contend with urban soils contaminated with legacy Pb. Founded in 1991 on the belief that everyone has the right to fresh, healthy, affordable food, TFP works to transform the food system into a more just, community-engaged model that supports food security for all while connecting diverse communities to each other and to the land (The Food Project, n.d., About Us section). Ever-changing levels of Pb in the product delivered to urban farms complicates TFP's access to usable compost. In the early 2000s, the City of Boston adopted a municipal composting program as a waste management solution to divert 35% of compostable waste from landfills (Recommendations of Boston's Zero Waste Advisory Committee, 2019), which also had the benefit of transforming organic waste (Ayilara et al., 2020) into a medium that can enrich nutrients, amend contaminated soil, and serve as cover material to reduce resuspension (Brown et al., 2016; Murray et al., 2011; Tandy et al., 2009). Over the course of this study, Boston municipal compost has exhibited a mean Pb concentration of 207 μg/g that is nearly three times the City of San Francisco soil and compost purchase standard value (from the revised California Human Health Screening Levels for Lead from the Office of Environmental Health Hazard Assessment, 2009) of 80 μg/g (Lupolt et al., 2022). This exceedance of the City of San Francisco compost standard, and variable total Pb concentrations year to year, has significant implications for urban farms in the Boston area, forcing farmers to make difficult choices about vendors and quality.

UA communities relying on compost often struggle to evaluate compost quality due to a lack of Pb concentration benchmarks and testing. To date, no federal benchmarks exist for compost Pb (Lupolt et al., 2022). In Massachusetts, residential surface soils (RCS-1, defined as soils at or within 500 ft of a residential dwelling, a residentially-zoned property, school, playground, recreational area or park; or within a groundwater resource area) have a regulatory limit of 200 μg/g while the EPA soil benchmark is 400 μg/g for a residential property or on the property of a child-occupied facility (Environmental Protection Agency, 2020; Massachusetts Department of Environmental Protection, 2020). It is generally accepted that these benchmarks do not reflect our current

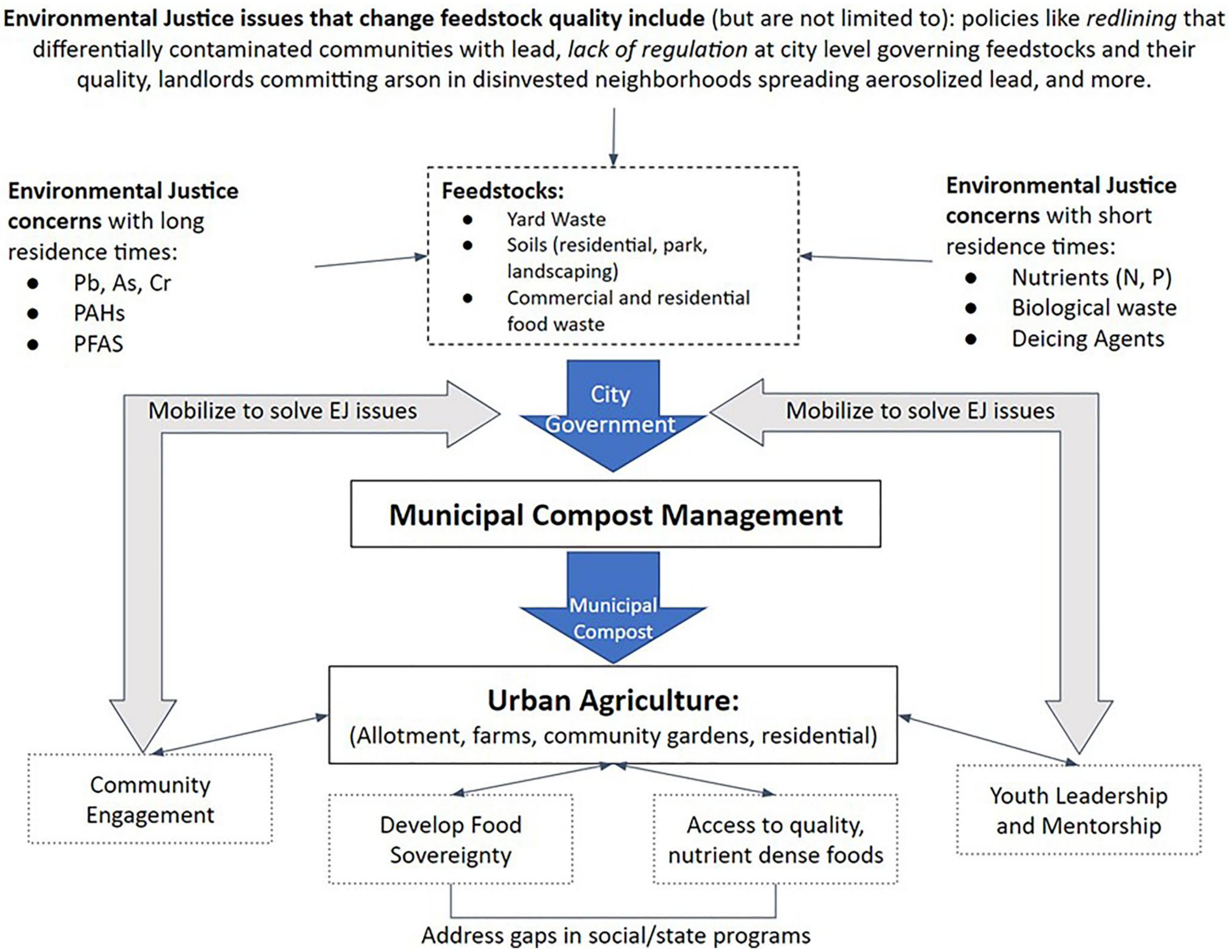

Figure 1. *Concept map of compost feedstocks, stakeholders, and potential outcomes in the urban agricultural movement*. Feedstocks range regionally and all have the potential to host contaminants with long or short residence times. While urban agriculture faces both structural and geochemical challenges, the movement's success gives rise to a broad array of societal outcomes including: increased community engagement and access to quality nutrient dense foods, and creating community-based youth leadership.

understanding of Pb toxicology (Lupolt et al., 2022; Walls et al., 2022). The 2021 US Court of Appeals for the Ninth Circuit found that the EPA did not appropriately create new regulations regarding lead-based paint or lead-soil hazards (U.S. Court of Appeals, 2021; Walls et al., 2022). Moreover, only half of the 40 most populous US cities had soil safety policies specific to UA (Lupolt et al., 2022). At both the state and federal levels, the regulatory framework for Pb in soil is both patchwork and out of date, with even less attention paid to compost, a matrix that is used in multiple contexts.

Previous work by our lab has demonstrated that urban compost can be contaminated with Pb in two ways: use of contaminated feedstocks in the production of compost and resuspension of Pb fines from contaminated soils (Clark et al., 2006; Fitzstevens et al., 2017; Sharp & Brabander, 2017). Further application to agricultural soils, especially in urban environments, can compound the effects from legacy Pb, adding additional Pb to already contaminated soils. Ratios of ^{207}Pb/^{206}Pb and ^{208}Pb/^{206}Pb implicate gasoline and paint as the dominant sources of urban soil Pb in Boston, demonstrating that old, fugitive Pb is contaminating new compost (Sharp & Brabander, 2017). For recent municipal compost, fine grain size fractions (<37 μm) have two times the Pb concentration of the bulk compost (Brabander et al., 2022). This suggests that particles with the highest Pb concentrations are also the most geomobile (transportable by natural processes in the environment) and must be managed to minimize resuspension. By evaluating Pb fate and transport pathways and collaborating with urban farmers, it is possible to develop best practices to foster safe UA.

Since Pb contamination and strategies to minimize Pb exposure remain key concerns for communities engaging in sustainable local agriculture, we have tracked bulk Pb concentrations in the City of Boston municipal compost starting in 2006. The long residence time of Pb in urban soils and compost make this issue persistent even though leaded gasoline and paint have not been used for decades (Figure 1). In this paper we (a) share a participatory framework for collecting and analyzing compost samples, (b) develop geochemical tracers to fingerprint different feedstocks and how they evolve over time as vendors and practices change, and (c) propose best practices developed with farmers to minimize Pb exposure while on the farm and in local neighborhoods. Urban compost will always be a hyper locally sourced matrix with distinct feedstocks and unique geochemical characteristics. Appropriate management strategies that are health protective must be geochemically informed and created in partnership with city agencies and urban farmers.

2. Materials and Methods

2.1. The Food Project Mission (TFP) and Urban Agriculture Challenges

Focusing their work in Boston's Dudley neighborhood and the city of Lynn, MA, TFP employs 120 teenagers annually to help grow 150,000 pounds of fresh fruits and vegetables, while also providing leadership opportunities and supporting them to create change in their own communities. The Food Project “envisions a world where youth are active leaders, diverse communities feel connected to the land and each other, and everyone has access to fresh, local, healthy affordable food.” (The Food Project, n.d., About Us section). In the past 29 years, TFP has cultivated 5,000,000 pounds of produce on 70 acres of urban and suburban land (The Food Project, n.d., Statistics section). The Food Project relies on compost to cultivate fresh produce and realize their vision of fresh, local, healthy affordable food for all by supplementing nutrients in urban soils, filling raised beds, and limiting heavy metal mobility (Fitzstevens et al., 2017; Pini et al., 2012; Sharp & Brabander, 2017). This reliance on locally sourced high quality compost to engage youth and transform communities has often left TFP with difficult choices (see Voices From the Field text box).

Voices From the Field

Compost and Urban Farming. Compost is the lifeblood of UA transforming yard waste and food scraps into filled raised beds, a method to dilute or cap lead in soils, and amendment for nutrient deficient soil. However, urban farms often don't have a great deal of choice when it comes to compost available to them. Since 2006, TFP has used four different municipal compost vendors to supplement compost generated on the farm. The quality of this compost can vary in nutrient content, porosity, and lead concentrations due to the variable feedstocks that vendors are provided with. Even without collaborating with a geochemistry lab, farmers can observe how plants respond to the compost—assessing its texture, porosity, nutrient content, how much of it was food waste—and determining the success of that year's crop.

Quality concerns. Farmers are anxious about variability in quality even from delivery to delivery (even on the month-to-month scale). At the TFP farm they see a fair amount of variability in the quality of the compost from the perspective of nutrients—which leaves farmers wondering about the “invisible” qualities of which lead is one. Educated farmers understand each test is just a snapshot of that particular moment, and does not mean that we can expect the same results in a later load.

Difficult choices (cost, Pb concentrations, and relationships with vendors). Farmers struggle with the decisions over what vendors to work with—they have to be thinking about lead and garden safety—and we're also thinking about a material that can be trusted to support healthy growth of plants. Ideally we find vendors that check both those boxes—but when they do they tend to be priced at a premium level, and finding a price point that makes sense for our grants can be challenging.

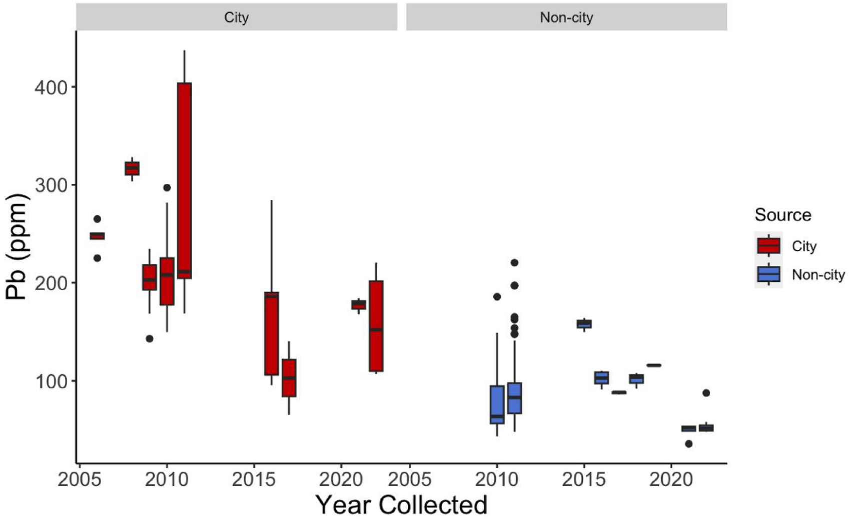

Figure 2. *Pb concentrations in compost from City (City of Boston) and non-city sources*. The number of samples per year differed depending on availability, where the total samples analyzed were 134 city and 97 non-city. Non-urban sources involve feedstock like food, loam mix, and regular compost. Note that the gap in 2013–2014 is due to a halt in the City of Boston's compost program due to high Pb. In 2020, no sample was collected due to the global COVID-19 pandemic. The mean Pb concentration for city samples across all years is 207 and 94 μg/g for non-city samples. Lines in boxes represent the median and dots represent outliers.

2.2. Participatory Action Research Model (PAR)

Even before Participatory Action Research (PAR) was popularized as a model for community group-academic-municipal interactions, we strived to break away from the traditional researcher-researched dichotomy, and instead sought to build power with community members through collective empowerment and meaningful action toward community member's goals (Baum et al., 2006; Gallagher et al., 2020; Hayhow et al., 2021). PAR research models bring practitioners and community members together to identify a public health concern or opportunity and remain engaged during the entire research process (Hayhow et al., 2021). Scientists enter the system to develop analytical methods and conduct research that addresses community members' questions and look for ways to connect with other decision makers and stakeholders in the system (Gallagher et al., 2020). A critical part of the model is communication and feedback among researchers and community members in varied and accessible ways. The PAR Flashlight Model, which was developed in collaboration with TFP, shines light on a wider range of both actors and audiences to instigate systemic community transformation (Gallagher et al., 2020).

Since 2006 our partnership has consisted of a mix of research, education, mentoring, and outreach, and action. More than 1,000 raised beds have been constructed in the Roxbury/Nubian Square neighborhoods through a “build a garden” program run by TFP youth interns (DIRT crew). Some of the educational and outreach actions include: (a) biannual workshops with TFP's DIRT Crew, where undergraduate lab members from Wellesley College help facilitate teaching DIRT Crew about Pb, its health effects, and test DIRT Crew member's soil, and (b) soil testing days, where undergraduate lab members help test community members soils at Garlic Fest, providing real-time Pb concentrations and discussing low-cost amendments if necessary. In addition to educational interactions focused on youth leadership through UA, our lab has conducted site evaluations for new gardens, producing geographic information system (GIS) maps and infographics to aid in farm planning and construction.

2.3. Sample Collection and Preparation

All compost samples were collected in collaboration with TFP. Samples were taken from piles delivered to the urban farm to best evaluate the metal inventories of materials that were actively being used by TFP and the neighborhood gardeners they support. These piles are often covered with tarps to minimize biological or chemical interactions with the immediate surroundings between time of delivery and actual use. Non-city compost samples were collected from piles of commercial compost-loam and commercial food sourced suppliers delivered to TFP's urban farm. In Figure 2, our "city" samples were collected beginning in 2006, and are from the City of Boston contracted vendors. Samples designated as "non-city" came from compost-loam mix and commercial food sourced compost from the suburban Boston area, which we began sampling in 2010. While the number of samples measured per pile varied from year to year, on average 2–3 samples/pile were analyzed in triplicate resulting in 5%–10% variability in measured lead concentrations. This suggests that a subsampling resulted in a representative analysis of the bulk sample. Typically, 4–6 L of compost are sampled using a garden trowel and placed in ziplock bags for transport to the lab. There, they are dried to constant mass either in a chemical fume hood when speciation work is planned, or in a 60°C drying oven when only bulk metal inventories are required. Over the course of the study and for a variety of different compost vendors, we fractionated several samples using plastic and nylon sieves sets (no brass standard sieves were used due to concerns about contamination during sieving). Before sieving, large pieces of anthropogenic materials (paper, plastic, and even occasional alkaline batteries) as well as larger (1–4 cm) stones and sticks were removed by hand and disposed of. The remaining sample was ground in a tungsten carbide mixer for a maximum of 4 min. The resulting homogeneous fine powers were then assembled into triplicate 32 mm X-ray fluorescence (XRF) sample cups (Premier Lab Supply) using 4 g of material, polyester fiber baffling, and 4–6 μm thick mylar XRF film (Premier Lab Supply).

2.4. Chemical Characterization

Field screening and in-situ elemental analysis of compost piles on TFP's two main farm locations were measured with a field portable Thermo Scientific NITON® XL3T 600 XRF analyzer. This helped assess pile scale heterogeneity, guided sampling, and provided the master farmer with real-time estimates of Pb concentrations. In situ rapid field analysis can guide decision making about compost use while more precise and accurate lab-based measurements are pending. The triplicate samples were run on a Spectro Analytical XEPOS 1 (from 2006 to 2018) and on a Spectro Analytical XEPOS He (from 2019 to 2022) (Kleve, Germany). Samples were analyzed in batches of 10 with NIST 2709a and NIST2709 SRM bracketing the unknowns. No corrections factors were applied to the measured samples as the standard deviation of the measured standard for Pb always fell within the accepted value. The average precision for individual measurements of the NIST 2709a standard was ±2% over the course of the study.

2.5. Size Fractionation of Compost

Approximately 1.0 kg of bulk compost samples were dry sieved using 9″ plastic sieves with stainless steel wires down to 37 μm, when Chemplex Nylon mesh screens were used. Samples were sieved into >2 mm, 2 mm to 250 μm, 250–125 μm, 125–63 μm, 63–37 μm, and <37 μm fractions. All sieving took place in a chemical fume hood. Only the >2 mm, 2 mm–250 μm and 250–125 μm fractions were ground prior to analysis, and samples <125 μm were homogeneous enough to not require grinding. Typical percent recovery was >95% with each size fraction yielding enough mass to construct XRF sample cups with 4 g (consistent with the bulk sample analyses). All size fractions were analyzed using XRF.

2.6. Data Reduction and Statistics

For principal component analysis (PCA), only elements above the XRF detection limits for all samples were included. All statistics were done in R, using packages: tidyverse, ggplot2, devtools, readr, plotrix, ggsci. All scripts and data sets used are publicly available on Github, and access to these resources is in the References. For PCA, only elements above the XRF detection limits for all samples were included.

3. Results

Bulk and trace element chemistry of city (municipal) and non-city (suburban) compost samples were collected in partnership with TFP from 2006 to 2022 in order to: (a) track bulk Pb inventories over time, (b) geochemically fingerprint feedstock sources and correlate with bulk Pb concentrations, and (c) document the presence of higher Pb concentration in wind transportable fractions than in the bulk matrix.

3.1. Bulk Pb Inventories Over Time

Using this decadal data set, we can assess both the effects of feedstocks on bulk Pb in compost and the potential for (re)contamination from legacy Pb in soils and air as the City of Boston has changed vendors. For City of Boston compost, the initial years of the program were marked with relatively higher Pb levels, especially in 2011 and 2012, when Pb levels exceeded the US EPA soil limit of 400 ppm, and the program was temporarily suspended (Figure 2). After 2015 with a new vendor, a greater reduction in Pb concentrations in city sourced compost was observed (Figure 2). Non-city compost samples on average had 2.2 times (Welch's t test, $t = 4.59$, df = 11.5, p-value = 0.000682) lower bulk concentrations than city samples over the period of study. The suburban compost also displayed less variability in Pb concentrations in any given year (e.g., greater consistency) and the bulk Pb concentrations are often at or below the California Human Health Screening Levels for Lead from the Office of Environmental Health Hazard Assessment of 80 μg/g (Lupolt et al., 2022).

3.2. Geochemical Fingerprinting of Source

Using XRF techniques for bulk chemical characterization of compost matrices yields a large matrix of both major and trace elemental concentrations information that is well suited for evaluation using PCA techniques.

Here, PCA is used as an exploratory tool to identify potential geochemical fingerprints by calculating each element's correlation with all other elements and mapping it onto a two-dimensional space, where the ellipses (Commercial Food Waste, Compost/Loam Mix, and Municipal City Vendors) describe waste stream elemental associations (Figure 3). Pb and Zn are the primary elements associated with the city vendor produced compost while the elements associated with loamy soils (Al, Si, Fe, K) define the suburban compost/loam sourced materials. Commercial food sourced compost shows the effects of amending this matrix with calcium, which is a common local practice (Fitzstevens et al., 2017). From this exploratory approach, unique element/element ratios used in Fitzstevens et al. continues to be an effective way to geochemically differentiate between sources.

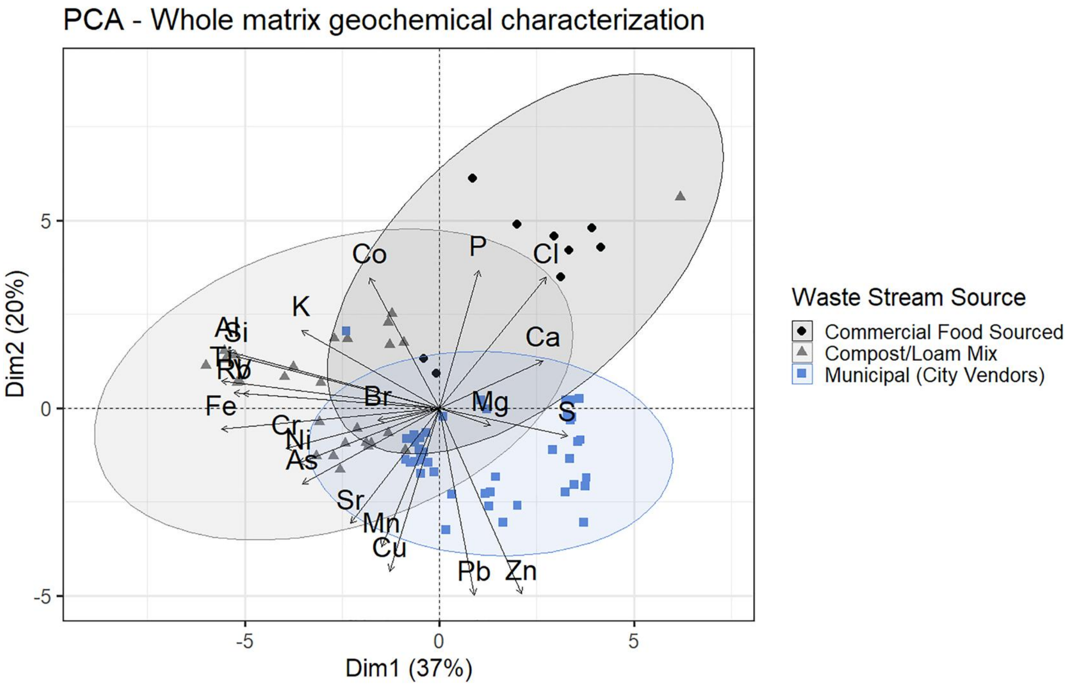

Figure 3. *Principal component analysis (PCA) Whole matrix geochemical characterization*. Note that each waste stream has a distinct association of elements defining the variance within the matrix. Fifty-seven percent of the system variance was preserved with these two principal component analyses.

Based on work by Fitzstevens et al. (2017), we use Si/Ca ratio on the *x* axis and Pb/Ti ratios on the *y* axis to capture variation in mineral content and Pb sources. Loam rich samples will contain feldspars and quartz and have a higher Si/Ca than compost samples. Pb/Ti differentiates between the two primary sources of Pb to urban soils (leaded gasoline and lead paint which often had added titanium dioxide) which was confirmed using Pb isotope analysis (Sharp & Brabander, 2017).

City compost consistently has high Pb/Ti values and relatively low Si/Ca values (Figure 4a). These high Pb/Ti values and generally low Si/Ca values suggest that Pb values are primarily determined only by the principae sources of Pb in the system: a mixture of aerosolized Pb paint and leaded gasoline with combustion sourced Pb being dominant. Compost from non-city sources contain much lower Pb/Ti and greater variability in Si/Ca which can be attributed to the more diverse sourcing of materials in suburban compost and overall higher mineral content.

Figure 4b tracks the changes in Pb/Ti and Si/Ca ratios in city compost during the period of study. Initially (2006–2015) compost samples had high Pb/Ti ratios and low Si/Ca values (<5) suggesting that the compost contained little soil and that the fugitive Pb was being derived from both leaded paint and gasoline. After 2015 the Si/Ca ratio rose, indicating that more soil began to become incorporated into the final product. We anticipate that this is from yard soil from street side pick up of residential compost bags which was introduced in 2015 (Jackman et al., 2018). The observed lower Pb/Ti support this hypothesis as well as that residential yard soils will be dominated by Pb sourced from paint which has higher Ti concentrations.

Figure 4c shows the geochemical variation in the non-city compost in which we present the data by source type (commercial food, suburban sourced compost, and loam mix). Here there is a systematic increase in Si/Ca ratio as the feedstocks range from commercial food to loam mix. This variation in bulk chemical composition is

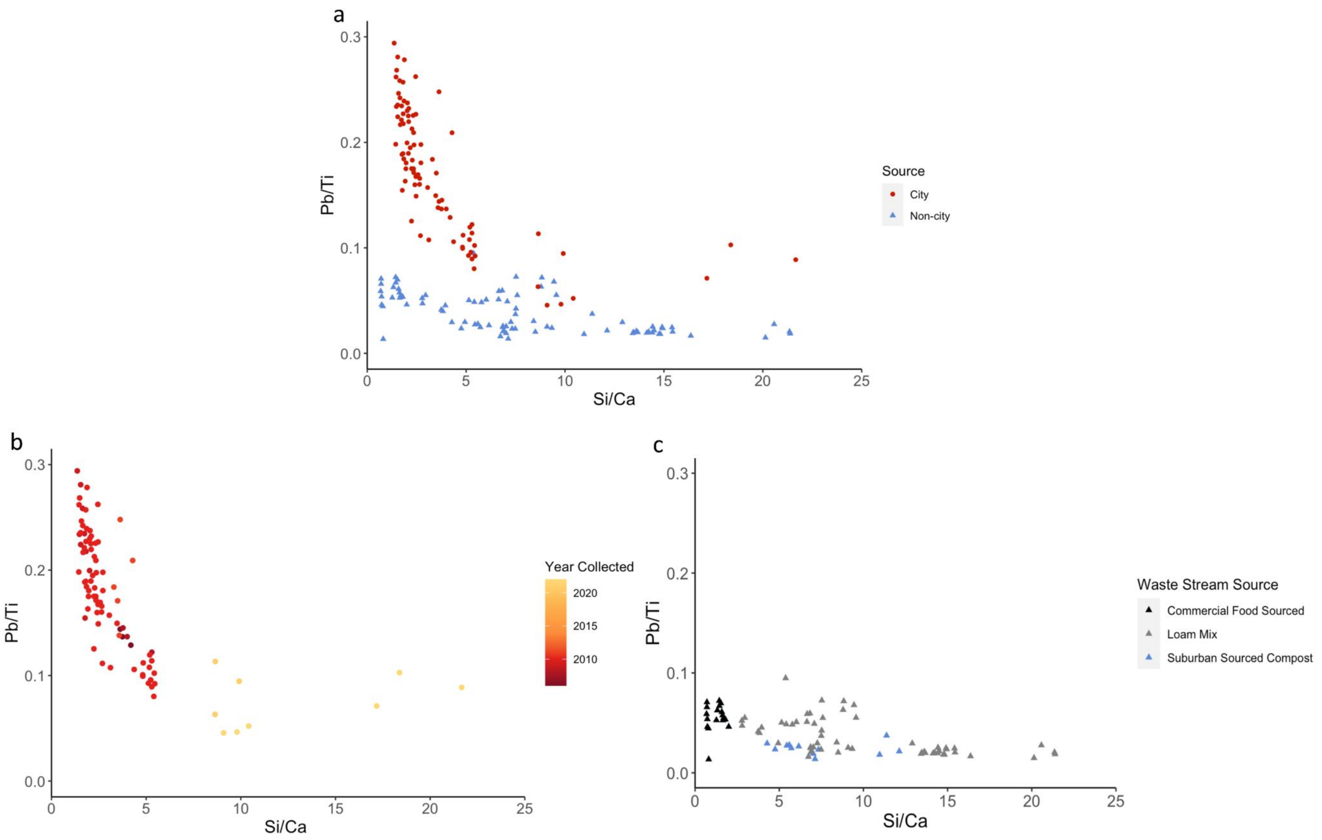

Figure 4. *Geochemical fingerprinting by comparing: (a) City of Boston vendor sources (red circles) versus non-city sources (blue triangles), (b) Change in Pb/Ti and Si/Ca ratios over time for city compost, and (c) Waste streams of non-urban source compost.* Ratio-ratio plots comparing major elements (Si and Ca) with trace elements (Ti and Pb) illustrate that compost matrices can be geochemically fingerprinted by source stream. These elements capture both variation in matrix composition and anthropogenic input.

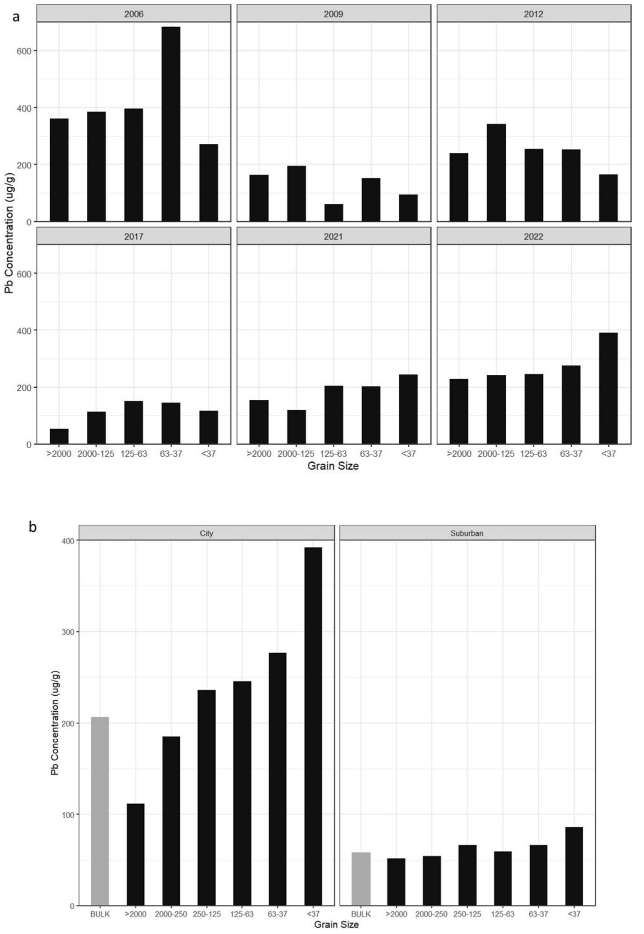

Figure 5. *Pb Concentrations in Size Fractionated Compost (a) from 2006 to 2022 (b) in City and Suburban settings in 2022.* Wind transportable fractions, <63 μm (Gillette & Walker, 1977; Gillings et al., 2022; Hayes & Ramos, 2019; Schaider et al., 2007) generally have higher Pb concentrations since 2017. Note that grain sizes <125 μm are considered easily transferable as they can stick to hands (Clark et al., 2008).

anticipated due to both the practice of adding Ca to commercial food sourced compost (Fitzstevens et al., 2017) and the increasing mineral content of the matrix and the compost becomes amended with loam.

3.3. Pb Reservoirs as a Function of Grain Size

Previous work demonstrated that Pb geomobility in this setting strongly correlates with soil particle size (Clark et al., 2008; Sharp & Brabander, 2017). To assess this correlation in compost, bulk samples of city compost were size fractionated. In city vendor compost we observe that Pb concentrations vary widely both over time and by grain size. We infer that some of these variations are linked with the changing feedstock composition (as illustrated in Figure 4), where a majority of Pb in compost is from wind transportable P(<63 μm; Gillette & Walker, 1977; Gillings et al., 2022; Hayes & Ramos, 2019; Schaider et al., 2007) Pb in soils (Sharp & Brabander, 2017). Before 2017 and the facility closure in 2013–2014, we note no discernible patterns either in bulk concentration or in how the Pb is partitioned among size fractions (Figure 5). This suggests that more than one fugitive Pb pathway is linked with elevated Pb concentrations in compost (e.g., both autochthonous and allochthonous contamination). For samples from 2017 and later, Pb concentrations in the finest three size classes (125–63 μm, 63–37 μm, and <37 μm) are higher than in the two largest size fractions (Figure 5a). Furthermore, in the most recent samples we see a clear trend of increasing Pb concentration as a function of grain size. These wind transportable grain sizes impact the characterization of exposure risks. In 2022, the <37 μm size fraction had Pb concentrations almost two times that of the bulk compost. This demonstrates the need for “end use” benchmarks that are not based simply on either phytoavailable Pb or on bulk Pb concentrations.

We note that fugitive Pb associated with the finer grain sizes is only a challenge for compost sourced and handled in the urban context. The Food Project has been (when financially and logistically feasible) sourcing some of their compost from suburban vendors. In Figure 5b we compare two compost samples delivered to TFP urban farm, one from a city vendor the other from a suburban vendor. We note that not only are the bulk Pb concentrations lower by a factor of four, but that the suburban sample does not display the same trend of increasing Pb with decreasing grain size. This further supports the claim that fugitive Pb in the city compost is locally sourced.

4. Discussion

Over the course of this study, municipal compost has had 2.2× more bulk Pb than compost sourced from suburban vendors, with a mean concentration of 207 μg/g. It also harbors a greater proportion of the Pb inventory in wind transportable fractions. This has implications for neighborhood scale mobilization of Pb and additional contamination of urban agricultural soils acting as secondary source of transported Pb. In the early 2000s, the Roxbury neighborhood had an average yard/garden soil Pb of 900 μg/g, with maximum levels reaching 3,700 μg/g Pb (Clark et al., 2006). While compost tends to have lower total Pb than soil, it has greater percent Pb bio-accessibility based on the default Integrated Exposure Uptake Biokinetic (IEUBK) model (Fitzstevens et al., 2017). However, the new Centers for Disease Control and Prevention Blood Lead Reference Value (CDC BLRV) of 3.5 μg/dL would require total soil Pb to be closer to 50 μg/g, and 30 μg/g in compost according to the IEUBK model with default bioaccessibility parameter adjusted to the measured values for this matrix (Fitzstevens et al., 2017; Sharp & Brabander, 2017). Without our PAR partnership, only a handful of costly samples might be sent to the state's agricultural testing lab per year, which often report phytoavailability/acid soluble Pb. While this is common practice for agricultural testing, phytoavailable Pb doesn't directly correlate with geomobility and human exposure pathways.

4.1. Compost Properties, Collection Protocols and Their Public Health Implications

Compost feedstocks and collection methods are key in controlling fugitive Pb in urban sourced compost. For example, the City of Boston has increased efforts to collect yard waste curbside. This city initiative has increased the potential for residential yard soil to "contaminate" the compost feedstock. We investigated this by determining the total amount of Pb found in a curbside yard waste bag collected in the Nubian Square neighborhood of Boston and found that a single bag contained 191,000 μg of Pb (see Table S1 in Supporting Information S1). Feedstock stream management is critical to minimizing Pb additions to compost. It should be noted that several cities no longer place street sweeping or even yard waste material into compost waste streams (Project Oscar, 2016). It is time to rethink how residential yard waste is collected in the urban environment. This is particularly critical in older neighborhoods with a high density of houses that still contain Pb paint. Many cities including Boston use leaf vacuums to collect leaf litter, which inevitably takes up soil particles (which contain high amounts of Pb, especially in fine, wind transportable particles; Clark et al., 2006, 2008; Fitzstevens et al., 2017; Sharp & Brabander, 2017). After sieving leaves collected from a composting facility to separate >4 mm and <4 mm, we found that sieving only removed 18% of the mass of the bulk sample, but removed 46% of the total inventory of Pb in the sample (see Figure S1 in Supporting Information S1). In the Greater Boston context, leaves often make up as much as 75% of the compost feedstock as they contribute vital K, Ca, and C to the final product and break down quickly (See Figure S1 in Supporting Information S1). Changes to collection procedures, for example, using a mix of manual and less aggressive mechanized collection (e.g., raking), or removal of Pb before it becomes part of the matrix, for example, "reverse sieving" leaves to remove Pb and soils from leaves before adding them to the compost, could reduce Pb in city compost (See Figure S1 in Supporting Information S1).

These changes in collection procedures have the potential to produce low concentrations of Pb. Geochemically fingerprinting both sources of fugitive Pb and bulk compost matrix characteristics in the Boston context (e.g., feedstocks ranging from food sourced to loam amended) can inform both management practices and interventions to lower the burden of fugitive Pb in locally sourced compost that supports UA without the need for less generally available Pb isotopic data. In suburban settings, new commercial management practices have been able to produce compost with 40–50 μg/g total Pb, however, these suburban suppliers are expensive and present a financial barrier to urban farmers. While municipal compost in Boston has lower Pb concentrations in recent years as compared to pre-2006 levels, the city has yet to achieve results similar to suburban compost. There is a demonstrated need to reproduce these management practices that minimize bulk Pb in compost in the urban context to sustainably support UA.

4.2. Designing Successful Long-Term Compost Programs to Support Urban Agriculture

Our long-term tracing reveals that municipal compost generated from urban organic wastes has avertible risks with proper management. This is particularly relevant as converting organic solid waste into compost underpins a large area of improvement for our current global waste management system. Food and green (plant waste) are great feedstocks for compost generation and they currently make up roughly 44% of global waste (Kaza et al., 2018). Roughly 2 million tons of organic waste goes to some form of landfill, and the byproducts of this process include nutrient run-off and release of hazardous air pollutants (Chen et al., 2020; Lubberding et al., 2012; Wiedinmyer et al., 2014). Composted material represents just 5% of total global waste that is treated and disposed of, while open dumping accounts for approximately 33%. In total, solid waste releases the equivalent of 1.6 billion tons of CO_2, accounting for 5% of global emissions in 2016 (Kaza et al., 2018). Food waste accounts for half of this solid waste (Kaza et al., 2018). Given the large proportion that organic wastes account for in terms of composition, and the little composting that is occurring, devoting efforts and setting guidelines to safely scale-up compost can reap large benefits. Maintaining and prioritizing public health objectives while doing so remains imperative. This starts by not only treating compost as a way to manage waste, but also as a foundational component of supporting sustainable and collaborative UA (See *Voices From the Field*).

Voices From the Field

Sustainable support of urban farming with locally sourced compost. Urban farmers *are* responding to elevated lead levels often encountered in the context of UA by building raised beds (1,000–2,000 have been built in the Dorchester/Roxbury neighborhoods of Boston in the past decade through a Build a Garden Program run by TFP). These raised beds along with larger block-scale farms are in constant need of compost to serve as both an effective growing media (either as soil amendment [on the farms] or as wholesale growth media [for raised beds]) and as a diluent/cover for more contaminated soils.

Need for a collaborative process to ensure quality. Farmers and their academic partners along with local city agencies need to collaborate to set appropriate quality benchmarks specific to compost. Using soil based benchmarks likely underestimates risk as bioavailability tends to be higher in compost than resident urban soils.

With benchmarks in place, there is a need for reliable local low cost long-term (sustainable) solutions that provide farmers with compost that can be used with confidence and is widely accessible to support the production of locally sourced community specific produce in communities that often lack both food security and food sovereignty.

While a recent push in compost programs has emerged around the world, composting in the US has not scaled up to the extent that it is common practice. Many programs seem to struggle with maintaining operations in the long-run, and the end product is not created with the aim of sustaining UA. This has most certainly been the case in Boston where there has been a series of failed vendor and suspended contracts associated with the City's composting program over the past two decades. This creates an environment where farm managers face an inconsistent supplier landscape and poor quality control (see Figure 2). Farmers rely on subsidized compost, giving them little leverage to demand higher quality compost out of concern that they may lose access to this resource.

Although regulations exist for ensuring minimal accumulation of heavy metals within commercial produce, little to none exist for farmers and field workers who are exposed to the growing environment. This is a regulatory oversight because workers are exposed to heavy metals through contact with the growing media (soil or compost) and possibly through inhaling fine resuspended soil particles (Filippelli & Laidlaw, 2010; Filippelli & Taylor, 2018; Lupolt et al., 2022; Zahran et al., 2013).

It is worth noting that even when chemically mediated Pb immobilizing interventions are taken such as phosphate addition (Miretzky & Fernandez-Cirelli, 2008), the focus is almost entirely on reducing the phytoavailable Pb rather than concern for those working in the fields exposed to fine soil and dust.

The growing urban carbon crisis presents an opportunity to rethink our current paradigm of burning, burying, or diluting carbon in urban systems, and instead to transform this carbon into a valuable resource. This can be accomplished through collaboration with all stakeholders (urban farmers, city planners, waste engineers, and city officials), to avoid the inherent externalities linked with current practices of viewing urban carbon only as a waste product. The consequences of both social injustices and geochemical properties of environmental contaminants can act over decades, and must be considered concomitantly to design sustainable and equitable inventions.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

- Data—The data sets used to generate this manuscript's figures are available through Github-Zenodo (Yang et al., 2023).

- Software—R was used to generate figures and perform statistical tests (R Core Team, 2022).The following R packages were used: tidyverse, ggplot2, readr, plotrix, ggsci (Lemon, 2006; Wickham et al., 2019; Xiao, 2023). The code to generate the relevant figures and statistical tests are provided (Yang et al., 2023).

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References

About Us | The Food Project. (n.d.). Retrieved from https://thefoodproject.org/about-us/

Attanayake, C. P., Hettiarachchi, G. M., Harms, A., Presley, D., Martin, S., & Pierzynski, G. M. (2014). Field evaluations on soil plant transfer of lead from an urban garden soil. *Journal of Environmental Quality*, *43*(2), 475–487. https://doi.org/10.2134/jeq2013.07.0273

Ayilara, M., Olanrewaju, O., Babalola, O., & Odeyemi, O. (2020). Waste management through composting: Challenges and potentials. *Sustainability*, *12*(11), 4456. https://doi.org/10.3390/su12114456

Baum, F., MacDougall, C., & Smith, D. (2006). Participatory action research. *Journal of Epidemiology and Community Health*, *60*(10), 854–857. https://doi.org/10.1136/jech.2004.028662

Biasioli, M., Grčman, H., Kralj, T., Madrid, F., Díaz-Barrientos, E., & Ajmone-Marsan, F. (2007). Potentially toxic elements contamination in urban soils: A comparison of three European cities. *Journal of Environmental Quality*, *36*(1), 70–79. https://doi.org/10.2134/jeq2006.0254

Boggs, G. L. (1998). *Living for change: An autobiography*. University of Minnesota Press.

Boggs, G. L. (2011). Detroit, place and space to begin anew In *The next American revolution: Sustainable activism for the twenty-first century*. University of California Press.

Brabander, D., Andrews, D., Hayhow, C., Mendez, L., Cessna, I., & Dricker, A. (2022). "Old" fugitive lead in new urban compost: A decadal study of geomobile Pb in city of Boston compost. *Geological Society of America Abstracts With Programs*, *54*, 5. https://doi.org/10.1130/abs/2022AM-383648

Brady, J. (1983). Arson, urban economy, and organized crime: The case of Boston. *Social Problems*, *31*(1), 1–27. https://doi.org/10.2307/800406

Brown, S. L., Chaney, R. L., & Hettiarachchi, G. M. (2016). Lead in urban soils: A real or perceived concern for urban agriculture? *Journal of Environmental Quality*, *45*(1), 26–36. https://doi.org/10.2134/jeq2015.07.0376

Bugdalski, L., Lemke, L. D., & McElmurry, S. P. (2014). Spatial variation of soil lead in an urban community garden: Implications for risk-based sampling: Spatial variation of soil lead in an urban community garden. *Risk Analysis*, *34*(1), 17–27. https://doi.org/10.1111/risa.12053

Chen, D. M.-C., Bodirsky, B. L., Krueger, T., Mishra, A., & Popp, A. (2020). The world's growing municipal solid waste: Trends and impacts. *Environmental Research Letters*, *15*(7), 074021. https://doi.org/10.1088/1748-9326/ab8659

Cheng, Z., Paltseva, A., Li, I., Morin, T., Huot, H., Egendorf, S., et al. (2015). Trace metal contamination in New York City garden soils. *Soil Science*, *180*(4/5), 167–174. https://doi.org/10.1097/SS.0000000000000126

Clark, H. F., Brabander, D. J., & Erdil, R. M. (2006). Sources, sinks, and exposure pathways of lead in urban garden soil. *Journal of Environmental Quality*, *35*(6), 2066–2074. https://doi.org/10.2134/jeq2005.0464

Clark, H. F., Hausladen, D. M., & Brabander, D. J. (2008). Urban gardens: Lead exposure, recontamination mechanisms, and implications for remediation design. *Environmental Research*, *107*(3), 312–319. https://doi.org/10.1016/j.envres.2008.03.003

Clarke, L. W., Jenerette, G. D., & Bain, D. J. (2015). Urban legacies and soil management affect the concentration and speciation of trace metals in Los Angeles community garden soils. *Environmental Pollution*, *197*, 1–12. https://doi.org/10.1016/j.envpol.2014.11.015

Court of Appeals for the Ninth Circuit. (2021). A community voice v. EPA, No. 19–71930, opinion.

Distler, S., & Saikawa, E. (2020). A new screening index to better target low-level lead exposure in Atlanta, Georgia. *Scientific Reports*, *10*(1), 18087. https://doi.org/10.1038/s41598-020-75000-0

Environmental Protection Agency. (2020). Lead in soil. Retrieved from https://www.epa.gov/sites/default/files/2020-10/documents/lead-in-soil-aug2020.pdf

Filippelli, G. M., & Laidlaw, M. A. S. (2010). The elephant in the playground: Confronting lead-contaminated soils as an important source of lead burdens to urban populations. *Perspectives in Biology and Medicine*, *53*(1), 31–45. https://doi.org/10.1353/pbm.0.0136

Filippelli, G. M., & Taylor, M. P. (2018). Addressing pollution-related global environmental health burdens. *GeoHealth*, *2*(1), 2–5. https://doi.org/10.1002/2017GH000119

Fitzstevens, M. G., Sharp, R. M., & Brabander, D. J. (2017). Biogeochemical characterization of municipal compost to support urban agriculture and limit childhood lead exposure from resuspended urban soils. *Elementa: Science of the Anthropocene*, *5*(0), 51. https://doi.org/10.1525/elementa.238

Gallagher, C. L., Oettgen, H. L., & Brabander, D. J. (2020). Beyond community gardens. *Elementa: Science of the Anthropocene*, *8*(1), 004. https://doi.org/10.1525/elementa.2020.004

Gillette, D. A., & Walker, T. R. (1977). Characteristics of airborne particles produced by wind erosion of sandy soil, high plains of west Texas. *Soil Science*, *123*(2), 97–110. https://doi.org/10.1097/00010694-197702000-00004

Gillings, M. M., Fry, K. L., Morrison, A. L., & Taylor, M. P. (2022). Spatial distribution and composition of mine dispersed trace metals in residential soil and house dust: Implications for exposure assessment and human health. *Environmental Pollution*, *293*, 118462. https://doi.org/10.1016/j.envpol.2021.118462

Hayes, S. M., & Ramos, N. A. (2019). Surficial geochemistry and bioaccessibility of tellurium in semiarid mine tailings. *Environmental Chemistry*, *16*(4), 251–265. https://doi.org/10.1071/EN18215

Hayhow, C. M., Brabander, D. J., Jim, R., Lively, M., & Filippelli, G. M. (2021). Addressing the need for just GeoHealth engagement: Evolving models for actionable research that transform communities. *GeoHealth*, *5*(12), e2021GH000496. https://doi.org/10.1029/2021GH000496

Jackman, E., Passaretti, M., Chia Yan Min, K., Sharp, R., & Brabander, D. (2018). Decadal Changes in City of Boston Municipal Compost: Identifying best management through geochemistry and participatory action research. *Geological Society of America Abstracts With Programs*, *50*(2), 311341. https://doi.org/10.1130/abs/2018NE-311341

Jean-Soro, L., Le Guern, C., Bechet, B., Lebeau, T., & Ringeard, M.-F. (2015). Origin of trace elements in an urban garden in Nantes, France. *Journal of Soils and Sediments*, *15*(8), 1802–1812. https://doi.org/10.1007/s11368-014-0952-y

Jung, K. H., Pitkowsky, Z., Argenio, K., Quinn, J. W., Bruzzese, J., Miller, R. L., et al. (2022). The effects of the historical practice of residential redlining in the United States on recent temporal trends of air pollution near New York City schools. *Environment International*, *169*, 107551. https://doi.org/10.1016/j.envint.2022.107551

Kaza, S., Yao, L. C., Bhada-Tata, P., & Van Woerden, F. (2018). *What a waste 2.0: A global snapshot of solid waste management to 2050*. World Bank. https://doi.org/10.1596/978-1-4648-1329-0

Kodros, J. K., Bell, M. L., Dominici, F., L'Orange, C., Godri Pollitt, K. J., Weichenthal, S., et al. (2022). Unequal airborne exposure to toxic metals associated with race, ethnicity, and segregation in the USA. *Nature Communications*, *13*(1), 6329. https://doi.org/10.1038/s41467-022-33372-z

Laidlaw, M., Mielke, H. W., & Filippelli, G. (2022). Comments on the Unequal airborne exposure to toxic metals associated with race, ethnicity, and segregation in the USA. Preprint. https://doi.org/10.13140/RG.2.2.16091.03367

Lee, C.-H., Wu, M.-Y., Asio, V. B., & Chen, Z.-S. (2006). Using a soil quality index to assess the effects of applying swine manure compost on soil quality under a crop rotation system in Taiwan. *Soil Science*, *171*(3), 210–222. https://doi.org/10.1097/01.ss.0000199700.78956.8c

Lemon, J. (2006). Plotrix: A package in the red light district of R. *R News*, *6*(4), 8–12.

Liang, J., Yang, Z., Tang, L., Zeng, G., Yu, M., Li, X., et al. (2017). Changes in heavy metal mobility and availability from contaminated wetland soil remediated with combined biochar-compost. *Chemosphere*, *181*, 281–288. https://doi.org/10.1016/j.chemosphere.2017.04.081

Lubberding, H. J., Valencia, R., Salazar, R. S., & Lens, P. N. L. (2012). Release and conversion of ammonia in bioreactor landfill simulators. *Journal of Environmental Management*, *95*, S144–S148. https://doi.org/10.1016/j.jenvman.2010.08.030

Lupolt, S. N., Santo, R. E., Kim, B. F., Burke, T. A., & Nachman, K. E. (2022). Urban soil safety policies: The next frontier for mitigating lead exposures and promoting sustainable food production. *GeoHealth*, *6*(9), e2022GH000615. https://doi.org/10.1029/2022GH000615

Massachusetts Department of Environmental Protection. (2020). 310 CMR 40.0000: Massachusetts contingency plan. Retrieved from https://www.mass.gov/doc/310-cmr-400000-massachusetts-contingency-plan/download

McBride, M. B., Shayler, H. A., Spliethoff, H. M., Mitchell, R. G., Marquez-Bravo, L. G., Ferenz, G. S., et al. (2014). Concentrations of lead, cadmium and barium in urban garden-grown vegetables: The impact of soil variables. *Environmental Pollution*, *194*, 254–261. https://doi.org/10.1016/j.envpol.2014.07.036

Miretzky, P., & Fernandez-Cirelli, A. (2008). Phosphates for Pb immobilization in soils: A review. *Environmental Chemistry Letters*, *6*(3), 121–133. https://doi.org/10.1007/s10311-007-0133-y

Morrison, D., Lin, Q., Wiehe, S., Liu, G., Rosenman, M., Fuller, T., et al. (2013). Spatial relationships between lead sources and children's blood lead levels in the urban center of Indianapolis (USA). *Environmental Geochemistry and Health*, *35*(2), 171–183. https://doi.org/10.1007/s10653-012-9474-y

Muller, C., Sampson, R. J., & Winter, A. S. (2018). Environmental inequality: The social causes and consequences of lead exposure. *Annual Review of Sociology*, *44*(1), 263–282. https://doi.org/10.1146/annurev-soc-073117-041222

Murray, H., Pinchin, T. A., & Macfie, S. M. (2011). Compost application affects metal uptake in plants grown in urban garden soils and potential human health risk. *Journal of Soils and Sediments*, *11*(5), 815–829. https://doi.org/10.1007/s11368-011-0359-y

Paltseva, A. A., & Cheng, Z. (2019). Geospatial analysis and assessment of garden soil contamination in New York City. *RUDN Journal of Agronomy and Animal Industries*, *14*(3), 239–254. https://doi.org/10.22363/2312-797X-2019-14-3-239-254

Pamuk, E., Makuc, D., Heck, K., Reuben, C., & Lochner, K. (1998). *Socioeconomic status and health chartbook, health, United States, 1998*. National Center for Health Statistics.

Pini, R., Bretzel, F., Sparvoli, E., Pezzarossa, B., & Scatena, M. (2012). Compost and wildflowers for the management of urban derelict soils. *Applied and Environmental Soil Science*, *2012*, 1–6. https://doi.org/10.1155/2012/832608

Project Oscar. (2016). Retrieved from https://www.boston.gov/departments/public-works/project-oscar

R Core Team. (2022). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. Retrieved from https://www.R-project.org/

Raymond, J., & Brown, M. J. (2016). Blood lead levels in children aged <5 years — United States, 2007–2013. *MMWR. Morbidity and Mortality Weekly Report*, *63*(55), 66–72. https://doi.org/10.15585/mmwr.mm6355a6

Sabir, M., Ali, A., Zia-Ur-rehman, M., & Hakeem, K. R. (2015). Contrasting effects of Farmyard Manure (FYM) and compost for remediation of metal contaminated soil. *International Journal of Phytoremediation*, *17*(7), 613–621. https://doi.org/10.1080/15226514.2014.898019

Saikawa, E., & Filippelli, G. M. (2021). Invited perspective: Assessing the contaminant exposure risks of urban gardening: Call for updated health guidelines. *Environmental Health Perspectives*, *129*(11), 1. https://doi.org/10.1289/EHP10376

Schaider, L., Senn, D., Brabander, D., McCarthey, K., & Shine, J. (2007). Characterization of zinc, lead, and cadmium in mine waste: Implications for transport, exposure, and bioavailability. *Environmental Science and Technology*, *41*(11), 4167–4171. https://doi.org/10.1021/es0626943

Sharp, R. M., & Brabander, D. J. (2017). Lead (Pb) bioaccessibility and mobility assessment of urban soils and composts: Fingerprinting sources and refining risks to support urban agriculture: Pb bioaccessibility in soil and compost. *GeoHealth*, *1*(10), 333–345. https://doi.org/10.1002/2017GH000093

Spittler, T. M., & Feder, W. A. (1979). A study of soil contamination and plant lead uptake in Boston urban gardens. *Communications in Soil Science and Plant Analysis*, *10*(9), 1195–1210. https://doi.org/10.1080/00103627909366973

Statistics | The Food Project. (n.d.). Retrieved from https://thefoodproject.org/statistics/

Tandy, S., Healey, J. R., Nason, M. A., Williamson, J. C., & Jones, D. L. (2009). Remediation of metal polluted mine soil with compost: Co-composting versus incorporation. *Environmental Pollution*, *157*(2), 690–697. https://doi.org/10.1016/j.envpol.2008.08.006

Walker, D. J., Clemente, R., & Bernal, M. P. (2004). Contrasting effects of manure and compost on soil pH, heavy metal availability and growth of *Chenopodium album* L. in a soil contaminated by pyritic mine waste. *Chemosphere*, *57*(3), 215–224. https://doi.org/10.1016/j.chemosphere.2004.05.020

Walls, D., Kinchy, A., Margalit, T., Ramírez-Andreotta, M. D., & Mauro, S. E. (2022). Confronting legacy lead in soils in the United States: Community-engaged researchers doing undone science. *Environmental Science & Policy*, *128*, 165–174. https://doi.org/10.1016/j.envsci.2021.10.035

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L., François, R., et al. (2019). Welcome to the Tidyverse. *Journal of Open Source Software*, *4*(43), 1686. https://doi.org/10.21105/joss.01686

Wiedinmyer, C., Yokelson, R. J., & Gullett, B. K. (2014). Global emissions of trace gases, particulate matter, and hazardous air pollutants from open burning of domestic waste. *Environmental Science & Technology*, *48*(16), 9523–9530. https://doi.org/10.1021/es502250z

Wilson, D. C., & Velis, C. A. (2015). Waste management – Still a global challenge in the 21st century: An evidence-based call for action. *Waste Management & Research*, *33*(12), 1049–1051. https://doi.org/10.1177/0734242X15616055

Wortman, S. E., & Lovell, S. T. (2013). Environmental challenges threatening the growth of urban agriculture in the United States. *Journal of Environmental Quality*, *42*(5), 1283–1294. https://doi.org/10.2134/jeq2013.01.0031

Xiao, N. (2023). ggsci: Scientific journal and Sci-Fi themed color palettes for 'ggplot2'. Retreived from https://github.com/nanxstats/ggsci

Yang, C., Hayhow, C., Jackman, E., Andrews, D., & Brabander, D. J. (2023). Dataset for Boston compost manuscript figures [Dataset]. Github-Zenodo. https://doi.org/10.5281/zenodo.7996439

Yeter, D., Banks, E. C., & Aschner, M. (2020). Disparity in risk factor severity for early childhood blood lead among predominantly African-American Black Children: The 1999 to 2010 US NHANES. *International Journal of Environmental Research and Public Health*, *17*(5), 1552. https://doi.org/10.3390/ijerph17051552

Zahran, S., Laidlaw, M. A. S., McElmurry, S. P., Filippelli, G. M., & Taylor, M. (2013). Linking source and effect: Resuspended soil lead, air lead, and children's blood lead levels in Detroit, Michigan. *Environmental Science & Technology*, *47*(6), 2839–2845. https://doi.org/10.1021/es303854c